SYSTEM ASPECTS OF SCANNING BEAMS FOR WIDELY DISTRIBUTED USERS*

Dean P. Kolba
M.I.T. Lincoln Laboratory
Lexington, Mass. 02173

ABSTRACT

Satellite communications in the allocated EHF bands, (i.e., several frequency segments from ~20 GHz to 50 GHz) has the potential for providing interference resistant communications to users employing small, mobile terminals. To realize this potential, advanced spacecraft technologies are required, such as uplink coverage through high gain directive beams, onboard signal processing, and downlink beam hopping.

Simultaneous worldwide uplink coverage could be obtained via many narrow uplink antenna beams which collectively cover the earth field-of-view. When worldwide communications traffic is low volume, a reduction in space segment impact can be achieved by using a few narrow uplink antenna beams to provide the required service. To minimize delays, these beams must be able to rapidly point anywhere within the field-of-view to cover individual users who require a channel for brief communications.

The agile antenna beams can be shared through demand assignment techniques. A multimode common transmission format can provide both data and control channels. The data channels are available at several rates to allow either full duty cycle data transmission or burst data transmission. With burst transmissions, a single beam can support multiple calls in a time division multiplexed fashion. The control channels are utilized in coordinating the use of satellite resources to efficiently meet the communications needs of the users.

This paper discusses the use of EHF satellite communicatons to provide service to widely scattered users. The use of control channels to request and coordinate service is described. Example control protocols are presented, and system performance is indicated.

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* This work was sponsored by the Department of the Air Force, the Department of the Navy, and the Department of the Army.

INTRODUCTION

EHF satellite communication systems have the potential for providing interference resistant communications to large numbers of mobile users [1, 2]. The cost effective realization of this potential requires system architectures in which service is provided through small and relatively inexpensive terminals. These terminals are generally characterized by small antennas and low transmitter powers. The space segment which supports these small terminals requires advanced satellite technologies, such as uplink coverage through high gain directive beams, signal processing on-board the satellite, and downlink transmission through high gain directive beams as described in [1] and [2].

A high gain directive uplink antenna beam on the satellite provides coverage over a region which is less than the earth field-of-view as seen from the satellite. Simultaneous worldwide uplink coverage could be obtained via many of these narrow beams which collectively cover the field-of-view. As the gain in these beams increases, a larger number are needed to cover the field-of-view resulting in an increased satellite impact. In many cases, simultaneous processing of all the beams is not necessary. When high volume traffic is localized in a few areas or when worldwide communications traffic is low volume, a reduction in spate segment impact can be achieved by providing processing for only a few of the uplink beams. When supporting low volume traffic from widely distributed users, the processed uplink antenna beams must point to individual users who require a channel for brief communications. To minimize delays, these beams must be able to rapidly point anywhere within the field-of-view in response to requests for communications service.

The use of EHF satellite communications to provide point-to-point calling service to widely scattered users is discussed in this paper. A brief system description is first presented. Then, the use of control channels to coordinate satellite resource sharing is described. Finally, example system operations are presented and performance is indicated.

SYSTEM DESCRIPTION

EHF satellite communication systems for mobile users are described in [1] and [2]. These systems use advanced spacecraft techniques such as high gain uplink and downlink antennas and signal processing on-board the spacecraft in support of small terminals. The high gain antennas allow the user's terminal to employ a small diameter antenna and low power transmitter. As the capabilities of the terminal are decreased, the required antenna gain on-board the spacecraft must increase, resulting in narrower beams [3]. Earth coverage is then obtained by utilizing a number of the narrow beams to cover the field-of-view.

The signal processing on-board the satellite [4, 5] can include a wide range of functions such as frequency dehopping/hopping, demodulation/remodulation, decoding/encoding, buffering, reformatting, and overall system control. Demodulation/remodulation processing effectively decouples the uplink and downlink allowing each to be designed separately. This permits a frequency division multiple access (FDMA) uplink signaling structure and a time division multiplexed (TDM) downlink signaling structure avoiding many of the limitations of transponder satellites. Individual user terminals can benefit from full duty cycle uplink operation while multiple users are accessing the satellite through FDMA. On the downlink, the TDM format allows the satellite power amplifier to operate at maximum efficiency while avoiding intermodulation difficulties.

With an FDMA/TDM architecture for the system, channel assignments for users consist of frequency slots on the uplink and time slots on the downlink. This is depicted in Figure 1 where the uplink and downlink resources are shown over one frame of duration T seconds. An FDMA uplink channel is routed into a TDM downlink time slot as shown.

The FDMA uplink allows user terminals to transmit full duty cycle if desired. This requires an uplink antenna beam to be pointed at the area the terminal is located in and to be processed in the spacecraft for the duration of the communications. To receive communications from multiple beam areas on the earth, multiple uplink antenna beams must be processed in the spacecraft. For hexagonally packed areas of coverage, the antenna must be able to point to N=7, 19, 37, 61, or 91 areas (for small to modest size antenna arrays) to cover the earth field-of-view [6] as shown in Figure 2 for N=19. The required value of N depends on the capabilities of the terminals. As N becomes large to provide more gain, the burden of providing simultaneous full earth coverage increases. If traffic patterns do not require full earth coverage, a reduction in satellite weight and power requirements can be achieved by providing service to only M of the N possible areas at a time [7].

When M is less than N, a method is necessary to determine which areas of the earth will be serviced at a given time. Efficient utilization of satellite resources (the uplink antenna beams as well as the uplink FDMA channels and downlink TDM slots) can be achieved through the use of a control scheme implemented with appropriate control channels. The control channels allow the satellite resources to be formed into appropriate communication channels and to be assigned to specific users on demand. The control channels also allow users to request reconfigurations of their communication channels if the need arises.

When communication transmissions on the FDMA uplink are full (or nearly full) duty cycle, service can be provided to M areas at a time. By providing additional transmission modes with burst rates greater than the data rates, additional areas may be serviced. For example, if two users are in two different beam areas on the earth and both have strong uplinks (i.e., have clear weather), they can both be serviced by one agile uplink antenna beam. Each user transmits with a burst rate twice his data rate and they time share the antenna beam.

Service to multiple areas on the earth is also provided by the downlink antenna. The downlink transmission is a single RF carrier time shared among the various receiving users. As each user's time slot occurs, the single downlink antenna beam is pointed to the beam area (see Figure 2) in which the user is located and the data is transmitted at a burst rate much higher than the data rate. The number of downlink beam areas need not be the same as uplink beam areas, but for convenience they are assumed equal in this paper.

CONTROL FLOW

The pointing of uplink and downlink beams requires control in a system serving distributed, mobile users. Control is also required for demand assignment of communication channels to allow efficient utilization of limited spacecraft resources. Control channels are required to carry the control information necessary to implement a control protocol.

The control channels can be formed in the same FDMA uplink channels and TDM downlink slots as communication channels using a TDM structure in these resources. Three types of control channels (labelled C_1 C_2 and C_3) can be formed as shown in Figure 3. The C_1 and C_2 control channels provide control information flow from the users to a central controller who has con over satellite resources. The C_3 channels provide control information from the central controller back to the users.

The C_1 control channels are paired with data channels in the FDMA uplink. These control channels are used to control the configuration of the channel during communications. For example, suppose user 1 in beam area A is talking to user 2 in beam area B. If the call is operating in a half duplex mode, then an uplink beam is pointed to area A to receive a transmission from user 1 while the downlink beam points to area B (during the appropriate TDM slot) so that user 2 can receive the transmission as depicted in Figure 4. If user 1 stops talking and user 2 wishes to talk, the central controller is notified through control channel C_1. The channel is then reconfigured with the uplink antenna on area B and the downlink antenna on area A allowing the conversation to flow from user 2 to user 1.

The C_2 control channels are used independently from the data and C_1 channels. During the C_2 portion of each frame, the uplink demodulator is being used for some other purpose unrelated to the call which is being handled in the same demodulator during the data and C_1 portions of the frame. The C_2 control channels are used to transmit control messages from users to the central controller. These control messages could be status reports or requests for service, and in general are unrelated to ongoing calls.

The C_3 control channels carry central controller responses back to the users. These responses could be acknowledgments, assignments, or system status messages. Particular control messages are sent down to the specific beam areas in which the receiving users are located. This aiming of messages on the downlink conserves downlink power by concentrating the transmission where it is needed. For control messages which must be received worldwide, the message is repeated in each beam area.

The control flow depicted in Figure 3 allows for efficient use of satellite resources in forming control channels. The C_1 and C_2 channels are formed using the same uplink hardware as the data channels. During the C_1 and C_2 portions of each frame, all the antenna beams are available for use with these control channels. This efficiently makes use of already available antenna beams without requiring additional antenna beams to be formed solely for use with full duty cycle control channels. The C_3 channels efficiently use satellite downlink power by aiming control messages to the specific areas where they are needed.

This control flow also provides flexibility to handle a wide variety of control protocols. The C_1 and C_2 channels provide a separation between reconfiguration requests and resource requests or status reports. This allows for efficient routing of these messages independent of where the central controller is located. If the central controller is based on-board the satellite or is based on the ground, the messages from C_1 and C_2 are sent to the controller and processed independently. (For a ground based controller, the C_1 and C_2 control channels are transmitted on the downlink. The controller also needs an uplink channel to transmit commands to the satellite and control responses for filling the C_3 downlink channels. These are not shown in Figure 3.) If the controller is split between the satellite and the ground, the C_1 control messages are read in the satellite for immediate reconfiguration action (such as repointing the uplink and downlink beams). The C_2 control messages are sent on the downlink for processing by the ground segment of the controller. In this split controller mode, the resource allocation decisions (channel assignments) are made and a user status data base is maintained on the ground. This removes the predominant controller burden from the satellite while maintaining good responsiveness to the reconfiguration requests sent on C_1 channels.

Additional flexibility is available in the C_2 control channels. All the FDMA channels are available for receiving control transmission during the C_2 portion of the uplink resources. As many of these channels as desired can be used for transmission of control messages. This allows the control capacity to be easily adjusted to fit the needs of the system. In addition, different channels can be used for different type control messages and with different protocols if desired. For example, some C_2 channels can be used with a random access protocol for resource request messages while other C_2 channels can be used with a dedicated access protocol for status report messages. The C_2 chaannels used for different purposes can even have control messages blocked into different lengths for added flexibility.

The C_3 control channels are also quite flexible. The number of TDM slots used for C_3 channels can be varied according to system needs. Different C_3 channels can be used with different protocols and different message lengths if desired. For example some C_3 channels can be used to regularly transmit system status or directory messages to each beam area in turn. Other C_3 channels can be used to transmit central controller responses to specific users in the area where they are located. The users know which TDM slots are used for each C_3 channel, and they monitor these channels for messages addressed to them.

Considerable flexibility is available in the control flow described. The amount of this flexibility utilized depends on the system requirements. Systems with slowly changing fixed assignment of channels or rapidly changing demand assignment of channels or both can be controlled by using the C_1, C_2, and C_3 control channels to a lesser or greater degree. Systems employing preemption capabilities can also utilize this control flow.

The control flow described here, augmented by bundling each data and C_1 control channel pair together for transmission in a slightly greater capacity TDM downlink slot, can also provide for the control of military network communications [8]. In this mode of operation, the C_1 channel may no longer require monitoring by the central controller. For systems in which network communications as well as point-to-point communications are supported by a common transmission format, the overhead necessary for transmitting C_1 channels with the data channels on the downlink results in only a small degradation for point-to-point calls which only need data on the downlink (e.g., 0.5 dB loss if 300 bps C_1 channels are bundled with 2400 bps data channels).

CALL OPERATIONS

A variety of point-to-point call services can be provided to the distributed users of the system. The calls can be half-duplex as shown in Figure 4 or they can be full-duplex. For full-duplex operations, a second circuit is set up providing a communications path from user 2 to user 1 in addition to the user 1 to user 2 path shown in Figure 4. The calls can be two party or conference calls. For example, in a half-duplex three party conference call, one party is talking while the other two parties are listening.

Full duplex calls involve the least amount of control. For full duplex operations, the data C_1, C_2, and C_3 channels are all used. The call is initiated by requesting a communications channel. The request message is sent to the central controller on a C_2 control channel in accord with the control protocol. For example, with random access C_2 channels, the caller waits until C_2 channels are available in his area (when an uplink antenna is pointed at his area during the C_2 portions of the uplink frames) and transmits his request into one of the C_2 channels. If no acknowledgment is received (e.g., if contention occurred), the caller must try again at some later time. The C_2 channels in this mode are time shared betweeen the N beam areas on the earth using the M uplink antenna beams available. As another example, with dedicated access C_2 channels, the caller waits until his assigned time slot in his assigned FDMA C_2 channel comes around and then transmits his request message.

After the central controller receives a request, an acknowledgment is sent to the caller using a C_3 channel to let the caller know the request was received. The controller then processes the request and decides whether an assignment or denial of a channel will be made. If the request is denied, the caller is sent a denial message on a C_3 control channel. If an assignment is made, the controller sets up the channel using satellite resources and then sends an assignment message to the caller and the called party. Upon receiving the assignment, each party acknowledges the assignment using the C_1 control channel. The users now have a full-duplex channel and can begin communicating . When done with the channel, they send hang-up messages to the controller using the C_1 channels.

In order to establish channels, a data base must be maintained containing information about where the called users are located. Although this data base could be maintained by the calling user it seems more appropriate for it to be maintained by the central controller. The data base can be as simple as a list of which users are at each terminal and which beam area each terminal is in. In this case, the central controller can connect the call to the proper terminal. A terminal controller or operator at the terminal then connects the call to the proper user port. If (in a simple data base) no terminal status information is maintained, then the central controller might first establish contact with the terminal to determine whether the call will be accepted or not before an assignment is made. If the central controller maintains a detailed data base on the status of the terminals, a call can be connected all the way through to the correct destination user's port with no terminal controller to central controller handshaking.

For full-duplex calls operating with full duty cycle data transmissions (i.e., full duty cycle within the data portion of each frame), M uplink antenna beams can handle M/2 calls between distributed users. If several users happen to be in the same beam area, a single beam can provide service to all of them, and more than M/2 calls can be supported. Additional calls can also be supported if users can transmit their data at a higher burst rate on the uplink. In Figure 5, multiple modes for uplink transmissions are shown. During the data portion of each uplink frame, a terminal can transmit 1, 2, or 4 streams of data at rate R_D. In the $4R_D$ burst rate mode, the uplink antenna is needed for only 25% of the data portion of each frame to receive a data stream of R_D bits per second. The remaining time, the antenna can be picking up traffic from other areas of the earth. In addition, these uplink modes allow more than one call to be handled by a terminal at the same time by providing the capability for transmitting multiple data streams from that terminal.

The C_1 and C_2 control channels are also shown in Figure 5. These channels operate with the same robustness as the R_D burst rate data channel and do not change mode of operation as the data channel burst rate increases. By not changing the mode of these channels, calls with mixed data burst rates (e.g., the calling user in the R_D mode and the called user in the $4R_D$ burst rate mode) can be more easily handled. Of course, multiple users at a terminal must share the C_1 and C_2 control capacity.

Half-duplex calls require a greater amount of control than full-duplex calls, but require half the system resources of full-duplex calls. The call requests and assignments are done in the same manner as for full-duplex calls. Once a half-duplex call is started, the users talk in turn by controlling the direction of data flow in the channel (see Figure 4). The control mechanism for controlling this direction of data flow is provided by push-to-talk indications from the users. These push-to-talk messages are transmitted to the central controller on the C_1 control channel as shown in Figure 6. Each user in turn transmits a P bit push-to-talk message on the C_1 channel while the uplink antenna is pointing at his area (during the C_1 portion of each frame). After dwelling on one area long enough to receive a complete message, the uplink antenna dwells on the next user's area for the C_1 portion of each frame until another message is received. At the completion of a cycle, the central controller has a push-to-talk indication from-each active user. Then, the controller can configure the channels appropriately for the next cycle. (In order to balance the load on the controller, the cycles from different uplink antennas can be shifted or subcycles can be formed so that decision making and switching for all users in the system do not have to be made at the same time.) One simple decision making scheme is to give the uplink of the channel to the user with his push-to-talk button pushed and in the case of a tie (both users pushing their talk buttons) keep the previous channel configuration. After reconfiguring the channel, the central controller informs the users of the change using the C_3 control channel.

CONTROL EXAMPLE

The use of the control flow described will now be illustrated by way of an example for some assumed system parameters and assumed control protocols. In this example, the number of uplink and downlink beam areas is N=61. Downlink service is provided by a single beam. Uplink service is provided by M=8 uplink antenna beams. On the uplink, 26 FDMA channels are used for control channels (as well as for point-to-point calls). Control protocols include both dedicated access and random access on the C_2 control channels and dedicated access on the C_1 control channels. On the downlink, 8 C_3 control channels are formed.

In this example, the control channels are structured into a common control frame. The control channels are all 300 bps channels. This requires 20% of the uplink frame for the C_1 and C_2 channels leaving 80% of the frame for data transmission (assumed to be at a burst rate of R_D, $2R_D$ or $4R_D$, with R_D =2400 bps). The control channels are used to transmit 45 bit messages (on C_1 channels) o r 90 bit messages (on C_2 and C_3 channels). The control channels and the 0.3 second control frame are shown in Figure 7. During a control frame, one control message can be sent on a C_2 or C_3 channel while two messages can be sent on a C_1 channel. For T=20 msec frames (see Figure 1), there are 15 frames in a control frame.

For this example, 24 of the C_2 channels are used as random access request channels. These channels are scanned over the 61 beam areas using 6 of the uplink antenna beams during the C_2 portion of each frame. Each antenna beam cycles through 11 beam areas (with 5 extra dwells spare) providing access to 4 request channels in each area. A cycle through the areas takes 11 control frames. Users of the system in each area have a random access request opportunity (in each of 4 channels) every 3.3 seconds. Contention can occur only between users in the same beam area if they transmit in the same channel during the same cycle. Users at the same terminal will always contend, in this case for their terminal's transmitter resource, if they attempt to transmit the same type of control message (C_1 or C_2) at the same time. Control message queues at the terminals can alleviate this type of conflict.

The other 2 C_2 channels are used as dedicated access report channels serviced through the remaining 2 uplink antenna beams (during the C_2 portion of each frame) in this example. One thousand terminals are provided status report message slots (90 bits), in a 2.5 minute cycle. The availability of these dedicated slots guarantees stability for the random access request channels. A user can make a request for service instead of a report in this dedicated slot. The maximum time to successfully submit a request is therefore 2.5 minutes in the unlikely event of severely congested random access channels in some beam area.

The eight C_3 control channels in this example can transmit about 27 messages (90 bits each) per second on the downlink. The messages can be acknowledgments, assignments, denials, system status, or preemptions as determined by the requirements of the central controller at the time.

The C_1 control channels are used on a dedicated access basis while calls are in progress. For example, suppose one of the uplink antenna beams is supporting 4 half duplex, two party calls. These calls are each assigned a separate uplink demodulator (this facilitates the handling of multimode calls). During the C_1 portions of the frame, the demodulators receive transmissions of push-to-talk messages to control half-duplex circuit turn around. The antenna dwells on each of the 8 users for half a control frame each, and they send 45 bit messages into the appropriate demodulators. After 4 control frames, the antenna repeats the cycle. Thus, every 1.2 seconds both parties in all 4 calls have the opportunity to turn their half-duplex channel around. The parties in the calls also transmit their hang-up messages in these channels.

CONCLUSIONS

Some system aspects of providing EHF satellite communications service to a large community of distributed users employing small, mobile terminals were presented. The service described was provided through a space segment which utilizes high gain uplink and downlink antenna beams and on-board signal processing. The efficient use of these satellite resources was achieved with resource sharing techniques implemented through a central controller. Control channels were described which provided the necessary control information flow between system users and the central controller. The control channels can be flexibly used for implementing a variety of control protocols to satisfy the specific operational requirements of the user community.

REFERENCES

1. Eaves, R. E., October 1979, "EHF Satellite Communication Systems for Mobile Users," EASCON, Washington, D.C.

2. McElroy, D. R. and Eaves, R. E., April 1980, "EHF Systems for Mobile Users," AIAA 8th Communications Satellite Systems Conference, Orlando, FL.

3. McElroy, D. R., "EHF System Concepts for Serving Mobile Users," AIAA 9th Communications Satellite Systems Conference, San Diego, CA (to be presented in March 1982).

4. Metzger, L. S., "On-Board Satellite Signal Processing," December 1978, NTC, Birmingham, AL.

5. Metzger, L. S., "On-Board Satellite Signal Processing," Volume I, January 1978, M.I.T., Lincoln Laboratory Technical Note 1976-41.

6. Dion, A. R., June 1979, "Minimum Directive Gain of Hopped-Beam Antennas," M.I.T., Lincoln Laboratory Technical Note 1979-33.

7. Eaves, R. E. and Kolba, D. P., "Multiple Beam FHF Antenna/Receiver Configurations for Unified Satellite Communications Uplink Coverage," AIAA 9th Communications Satellite Systems Conference, San Diego, CA (to be presented in March 1982).

8. Kolba, D. P., "Generalized Control and Networking for EHF Satellite Communications Systems," AIAA 9th Communications Satellite Systems Conference, San Diego, CA (to be presented in March 1982).

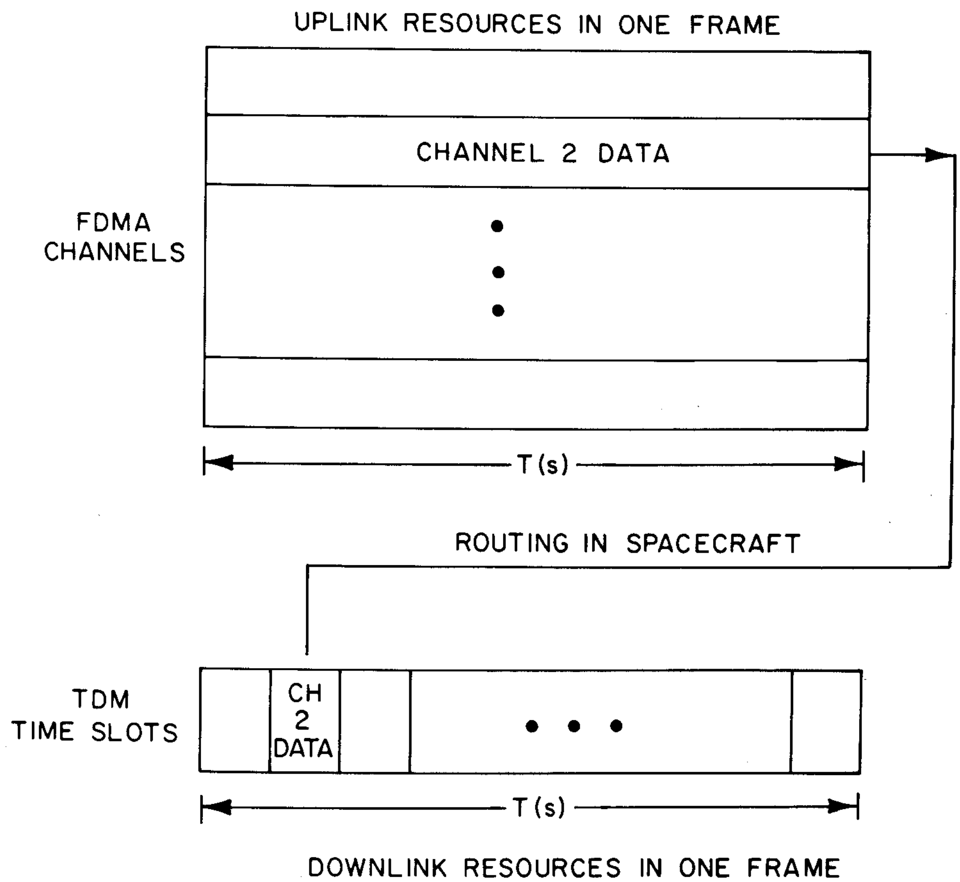

Figure 1. The formation of channels using FDMA uplink resources and TDM downlink resources.

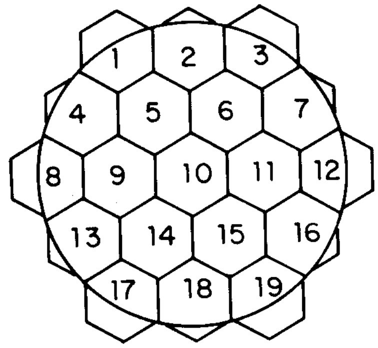

Figure 2. Earth field-of-view covered by N=19 hexagonally packed areas.

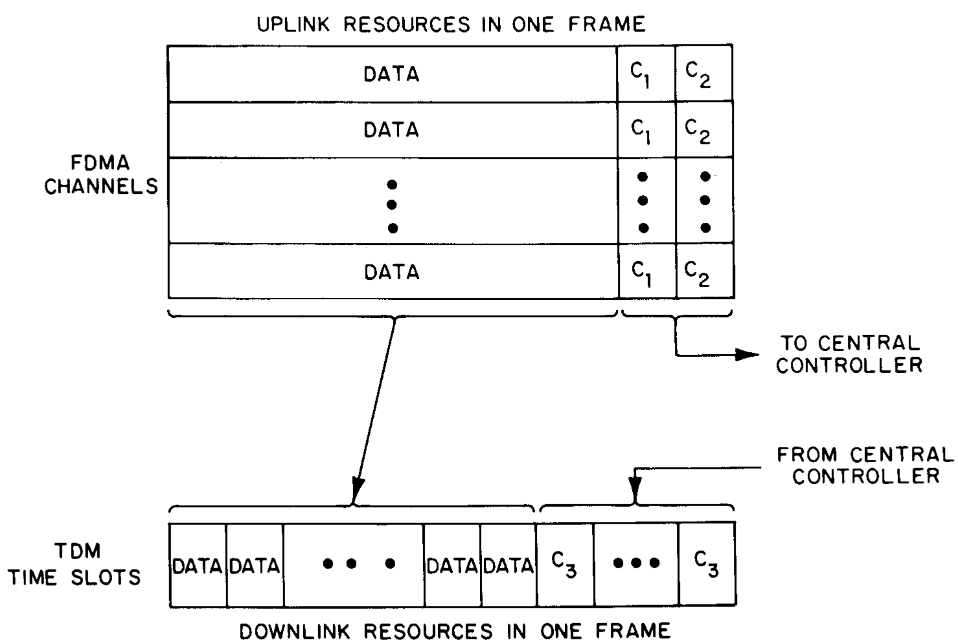

Figure 3. Partitioning uplink and downlink resources to form data and control channels. The control flow to and from a central controller is shown.

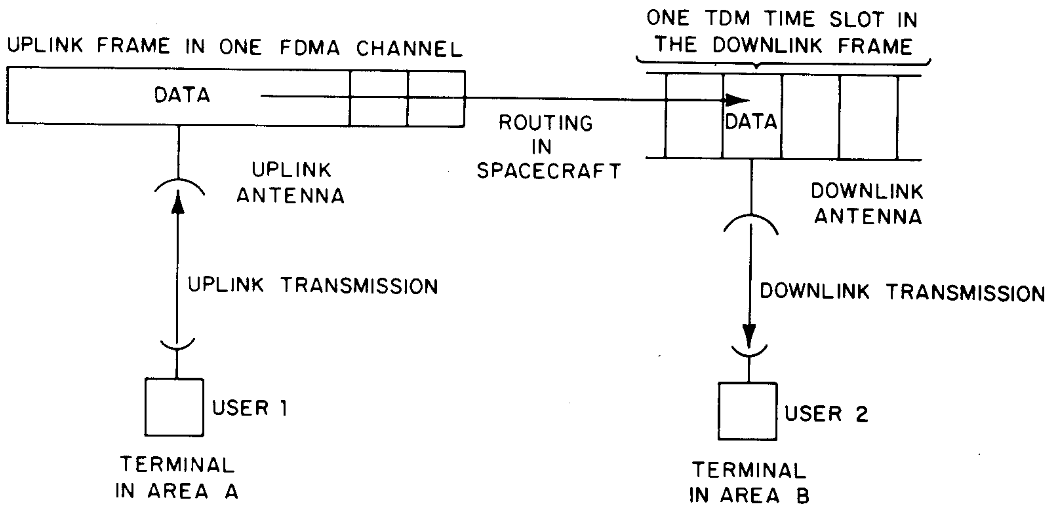

Figure 4. Operation of a half-duplex call with the transmission path from user 1 to user 2.

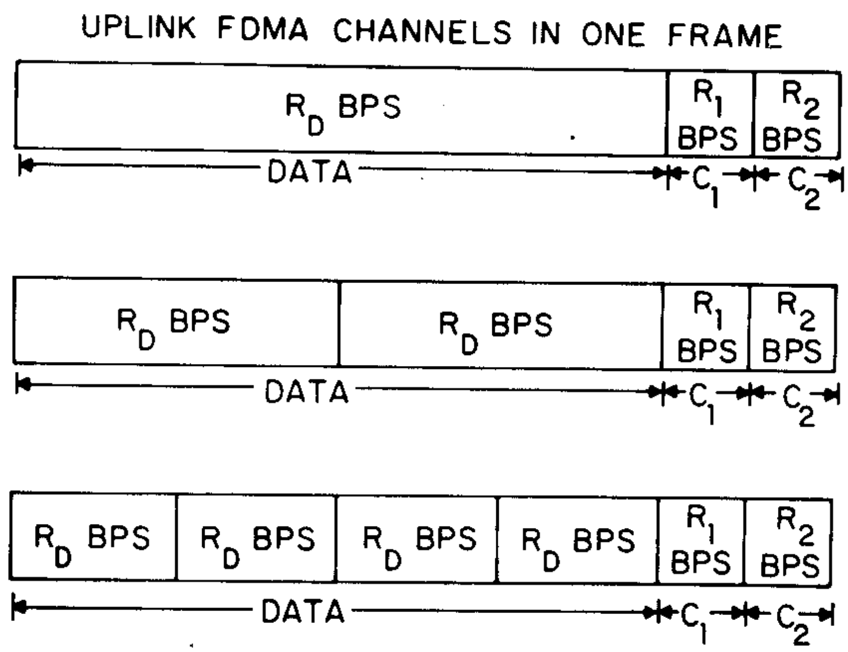

Figure 5. Uplink transmission modes for transmitting 1,2, or 4 data streams. The C_1 and C_2 control transmissions do not change.

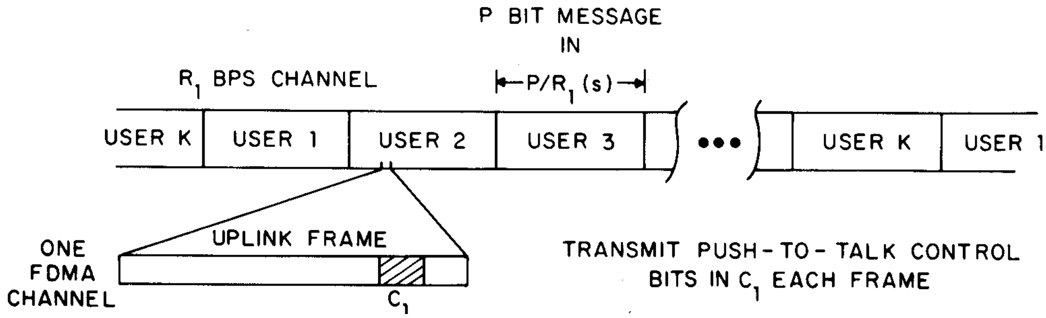

Figure 6. The usage of a C_1 control channel to transmit push-to-talk control messages to the central controller from users 1 to K in turn.

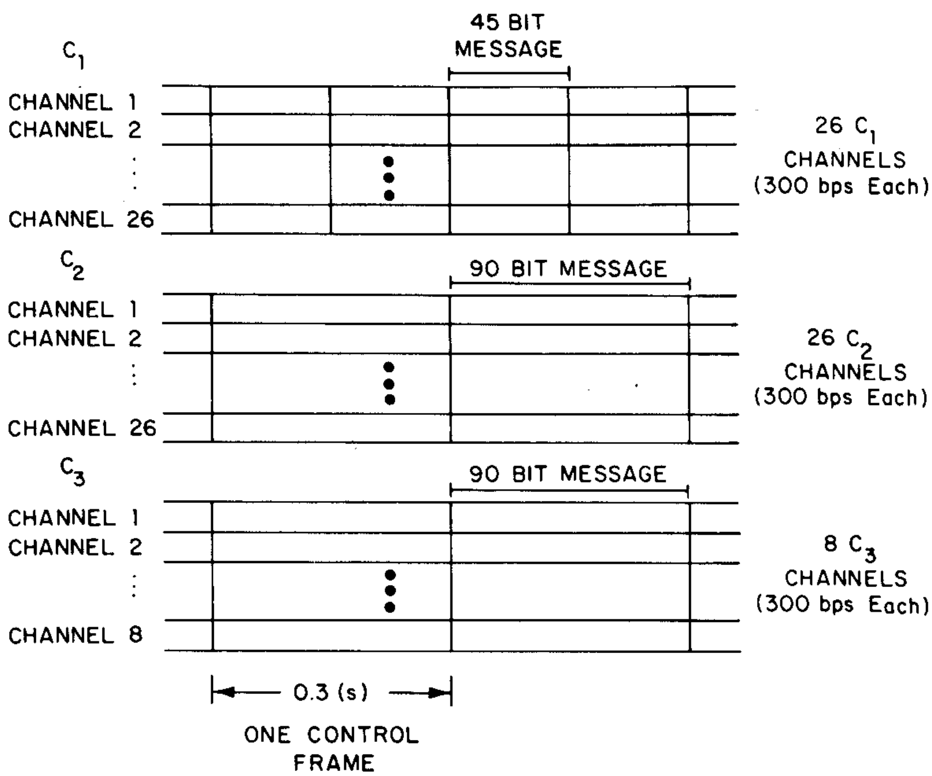

Figure 7. Example control frame for 300 bps control channels with 45 or 90 bit control messages.